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DETERMINATION OF SITE EFFECTS BY AMBIENT VIBRATION MONITORING

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SUMMARY

Site-effects may increase the response beyond the provisions of local Codes or Standards. Measurements that determine these effects can be of help to get the correct design input values and save considerable money in critical zones. The introduction of EC8 has brought considerable changes in the risk assessment in countries north of the Alps. In previous so called quiet zones earthquake is now the guiding design factor. For the huge stock of existing structures the assessment of a realistic risk becomes essential and economically important. This paper describes the SEISMID method which stands for Seismic System Identification. Based on both forced and ambient vibration tests, the response of the surrounding soil as well as the structure is monitored. Several sophisticated methodologies are combined in order to generate a valid risk map for the region as well as for local circumstances. The results are sophisticated microzonation-studies for cities, which are of interest to the community, as well as the detailed assessment of structures, which is of interest to the owners. A number of examples are available for demonstration. The quality of prediction will be discussed and compared to conventional approaches.

1. INTRODUCTION

Recent earthquake-scenarios in densely populated areas led scientist's attention on sophisticated seismic hazard prevention. Especially in urban areas, like the Vienna Basin, which are located predominantly on soft soil layer, waves of moderate seismic events can be major amplified. The enhancement of seismic exposure for local building structures, the so called site-effect, led to an ascending request for a precise investigation of the realistically seismic vulnerability.

Additionally earthquake hazard prediction has dramatically changed in last years. According to recent studies [Hinsch and Decker, 2003] scientists of the University of Vienna found out that different seismic slip rates of various sectors of the Vienna Basin Transform Fault (VBTF) indicate locked fault elements. They estimate that a strong-motion earthquake (at least Magnitude M = 6.1) can be expected to normalize the slip rate of the slowest sector of the VBTF to the rate of the fastest sector.

With regard to the economic and social importance (about 2.4 million inhabitants producing 45% of Austrian GDP) of the Vienna Basin area it will be strongly recommend to determine possible site-effects and furthermore enforce the proposed microzonation of that area to enhance the standard of seismic hazard analysis.

Additional to the increase in safety assessment, the proposed microzonation studies will lead to economic advantages regarding the conversion of national building regulations to the European Standards. Compared with the currently available national regulation ÖNORM B 4015 [ÖNORM B 4015, 2002] in the revised version of the Eurocode 8 [Eurocode 8, 2005] the subsoil classification scheme is more advanced and adjusted to local soil properties. In particular five different subsoil classes (A-E) are defined in Eurocode 8. Their distinguishing coefficient is the average shear wave velocity $V_{s,30}$ dominating in the first 30 m of the subsoil layers. It therefore will be necessary to have detailed information about the local site conditions, which currently is an exception or only available for relevant building structures. It therefore will be one of the primary objectives of the proposed

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method to get as much information as possible from the in-situ measurements, to enhance the basic principles and simplify the application of Eurocode 8.

2. PREVIEW

According to building regulations the probability of earthquake events in Austria is in comparison to the neighboring countries similar to those in Switzerland an substantially higher than in Germany. It is also noticeable, that the high populated areas in Austria (Vienna, Graz and Innsbruck) are located in higher endangered areas compared with the areas with high population density in Germany (Berlin, Munich, Hamburg) and Switzerland (Zürich, Bern), see Figure 1.

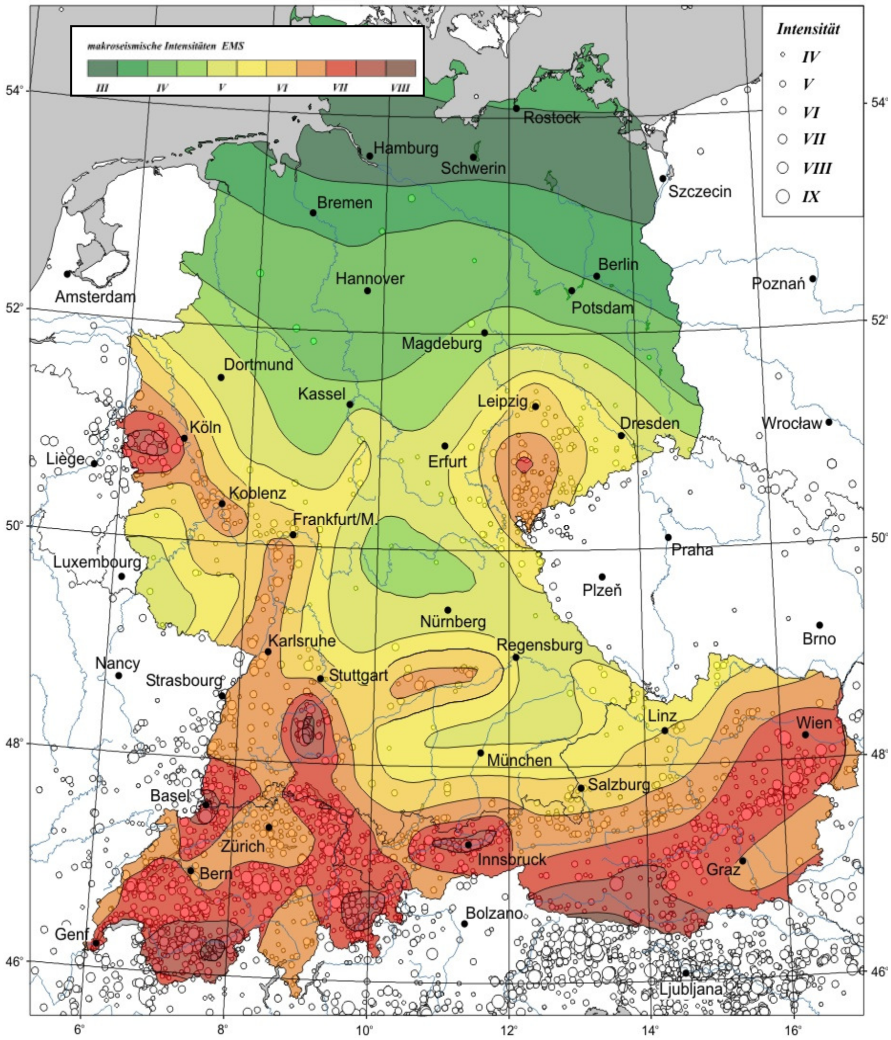

Figure 1: Assessment of earthquake hazard exposure for Germany, Austria and Switzerland, according to [Grünthal, Mayer-Rosa and Lenhardt, 1998].

Nevertheless, contrary to the neighbouring countries in Austria still no microzonation study exists. In recent year's extensive earthquake hazard analysis were accomplished in Germany, concentrated on the area of Cologne. Managed by the *GeoForschungsZentrum* Potsdam several tests were performed based on the H/V-Ratio and a critical frequency ratio between the natural frequency of the building structure and the subsoil, which led to a local earthquake hazard map [Merz, 2004].

In Switzerland high sophisticated research has been done particularly in the area of Basle. Numerous regulations and reports are available and indicate the high quality standard [Kind et. al, 2002], [BWG, 2004].

Supplementary to national research work several Europe-wide projects (SESAME, RISK-UE, SEISMOCARE …) have been accomplished and achieved an international standard in earthquake hazard assessment. The objective of this report is to develop a method for Austria, according to the existing European research work, to close the technological gap in seismic hazard prevention. The main advantages and high sophisticated technologies of these projects should be combined in the SEISMID-Technology. Therefore a short description of individual parts and work packages of these projects is given.

2.1 SESAME

The Europe-wide (Belgium, France, Germany, Greece, Italy, Norway, Portugal, Slovakia and Switzerland) SESAME Project (Site Effects assessment using ambient vibrations) [SESAME European research project, 2004] had the aim to estimate the site-effect with special attention on urban areas and low cost techniques. One of the objectives of the project was to investigate the reliability of the H/V and the array technique. During the project the influences of the experimental conditions on the results were studied and highlighted [Duval, A.-M., et al., 2004]. In an additional report [SESAME European research project WP12, 2004] user guidelines for the H/V spectral ratio technique on ambient vibrations are defined.
The very sophisticated conclusions of these investigations are a helpful input for experimental measurements of ambient noise as well as for the numerical data evaluation of the SEISMID-Project.

2.2 RISK-UE

RISK-UE [RISK-UE European research project, 2004] was a European project performed from 2001 until 2004, in which methodologies for earthquake-risk scenarios for several cities (Barcelona, Bitola, Bucharest, Catania, Nice, Sofia and Thessaloniki), including both current and historical buildings, were developed.
The project was based on seismic hazard assessment and stock-taking of buildings in order to identify the critical issues of urban systems. In the report of work package 2 [RISK-UE European research project WP2, 2003] deterministic seismic hazard evaluations for urban areas were developed, whereby attenuation relationships for European regions resulted. With application of slight modifications these approaches will be useful for the Vienna Basin Transfer Fault, in order to get the effective ground motion forces for the urban areas in Vienna.

2.3 SEISMOCARE

The SEISMOCARE European project [SEISMOCARE European research project, 1998] deals with computer aided reduction of seismic risk with application in existing cities. Its main aim was to develop an integrated methodology for earthquake hazard assessment and to produce a software package for reliable predictions of losses due to earthquakes.
The SEISMOCARE research work will be beneficial for the implementation of Geographic Information Systems (GIS) in the SEISMID project and should be an initiation for developing software packages for integrated seismic hazard prevention.

3. SEISMID - TECHNOLOGY

Local site conditions may affect adversely all of the important earthquake characteristics (amplitude, frequency content, duration), see e.g. [Kramer, S. L., 1996]. The dimension of the influence on the characteristics depends on the geometry and material properties of the building structure, the site topography and the input motion. Therefore numerous in-situ measurements, stock-tacking of existing buildings and adjusted earthquake attenuation relationships are required to get a realistic seismic hazard mapping. Additionally it is indispensable to find correlations between site response (and amplification factor respectively) and the soil conditions to consequently achieve the amplification factors from existing soil profiles.

3.1 In-Situ Measurement Procedure

Ambient vibration testing is a very attractive method for measurements in urban areas with moderate seismicity, because on the one hand the low ambient vibration amplitudes indicate better correlation with moderate seismic events (approximately linear-elastic constitutive material behavior) and on the other hand seismic cross-hole tests are complicated in urban areas because of the disruption of building occupants and induced damages on the building structure.
However forced vibration tests with a defined falling weight have exceptional advantages concerning the parameters of the subsoil layers. To get detailed information like layer thickness, shear wave velocity or dynamic Young's modulus it is indispensable to have a defined input-source to get a correct interpretation of the recorded

response. Thus both the ambient vibration method and the forced vibration technique seem to be very valuable for the SEISMID-technology.
In the following figure the forced vibration tests are described whereby the soil parameters can be determined. The refracted seismic waves are recorded by 3-dimensional geophones which are located in arrays on the subsoil surface. According to the theoretical fundamentals [Knödel, K., 2005] the distance between the geophones in the array has to be chosen in combination to the wave-numbers of the input signal. In Figure 2 the seismic impedance is denoted with I as the product of the wave velocity v and the soil density ρ.

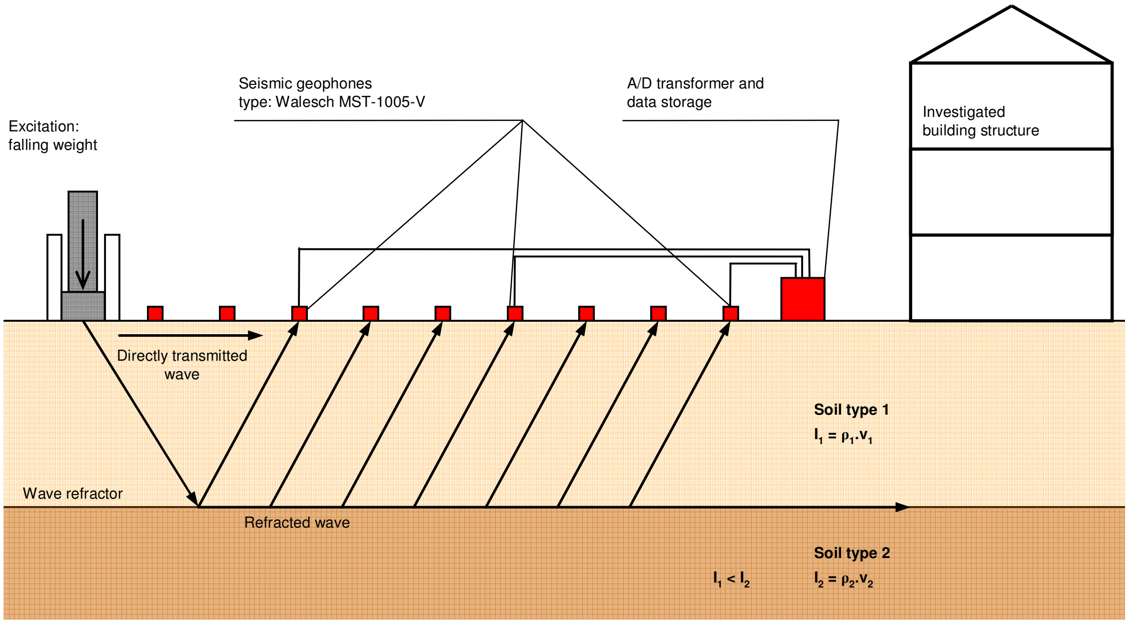

Figure 2: Seismic refraction method with proposed falling weight excitation.

In Figure 3 the H/V-Measurement installation is shown. Around the investigated building structure several 3-dimensional accelerometers are assembled to measure the ground response of the ambient excitation. The natural frequencies (and the mode shapes in case of multiple sensors) of the building structure are specified with internal 3-dimensional accelerometers.

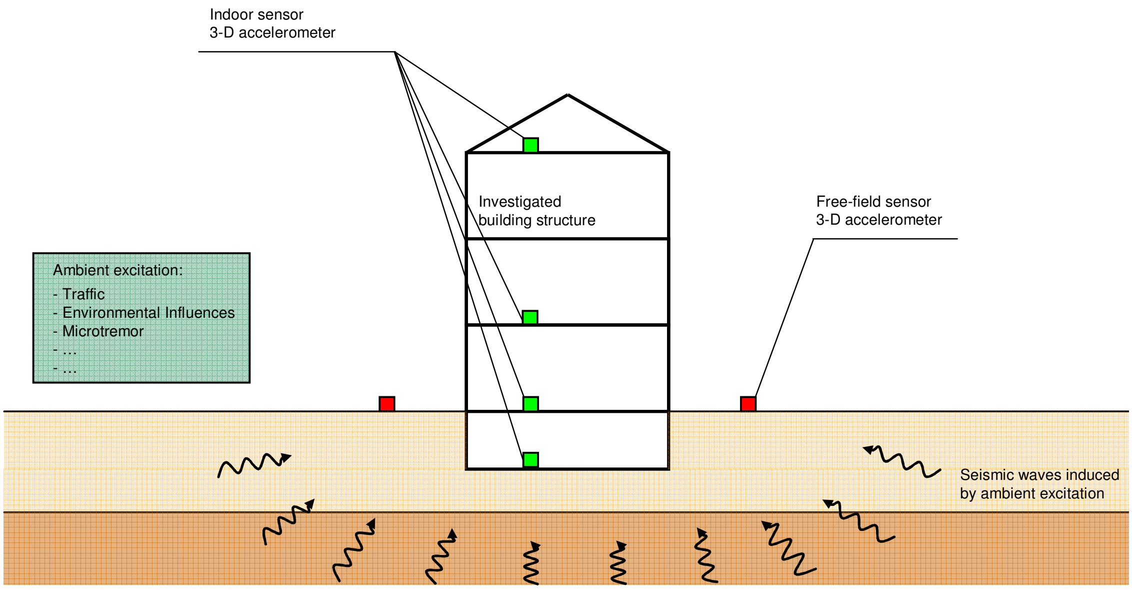

Figure 3: Instrumentation for ambient H/V-Measurements.

3.2 H/V Technique

To estimate the local amplification factor of seismic waves it is prevalent to use the H/V-Method according to Nakamura [Nakamura, Y., 1989] due to the fact that it is a very simple and user-friendly practice. The method is convenient for almost every region in Europe because it was successfully accomplished in countries with moderate seismicity where no strong motion data was available, see e.g. section 2. Therefore the input for the H/V-Computation can also consist of transient or even ambient excited signals.
Nevertheless in case of the amplification factor it is more beneficial to use ambient excitation, because the large number of samples which are needed for statistical evaluation would, in case of transient excitation, led to unacceptable disruption for occupants.
The ambient vibration technology for seismic microzonation was effectively applied in former projects, see e.g. the SESAME-project [SESAME European research project, 2004] or the Scientific Report of DNFK [Bormann, P., 2004].
With the proposed method [Steimen, S., Wössner, J., Fäh, D., 2005] the following local soil parameters can be defined:

- Basic natural frequency f_0 of the subsoil.

- With cognition of the basic natural frequency f_0, either the shear wave velocity V_S or the layer thickness can be calculated, if one of the both values is known. Because of the fact that by means of the proposed method neither the shear wave velocity V_S nor the layer thickness can be defined exactly, additional measurements have to be arranged, see section 3.3.

- Estimation of the amplification factor. The peak of the H/V-Spectra may not be transferred directly into an amplification factor. In several publications these value is interpreted as a lower limit value for the amplification of shear waves.

The computation and furthermore the numerical implementation of the H/V-Procedure can be described in order to the SESAME-project [SESAME European research project, 2004], as follows, see Figure 2:

- Pre-Processing:
  - 3-dimensional input (the accelerometer in northward direction to get North-South, East-West and vertical components)
  - Windowing of the signal (in our case only the ambient parts are of interest, obverse, in case of transient excitation only the transient parts of the time response are of interest)
  - Offset-removal

- Main Data-Processing:
  Hence the three different components of the signal were considered separately. The main data processing is repeated for every input-signal (n-Steps according to the numbers of preliminary separated windows).
  - Fast Fourier Transformation (FFT) is applied to obtain the several spectral amplitudes of the three components
  - Smoothing of the three spectral amplitudes with a bandwidth factor of 6
  - Afterwards the resulting horizontal component is evaluated on the quadratic average of the North-South and East-West component
  - The resulting H/V-Value is the logarithmized (on base 10) ratio of the resulting horizontal component and the vertical component

- Post-Processing:
  - The output of the data-processing (n-Signals) is accumulated and averaged over the number of windows.
  - To consider the experimental and numerical uncertainties the statistical standard deviation is calculated (in logarithmic scale).
  - Finally the averaged H/V-Ratio and the standard deviation are set back to linear scale.

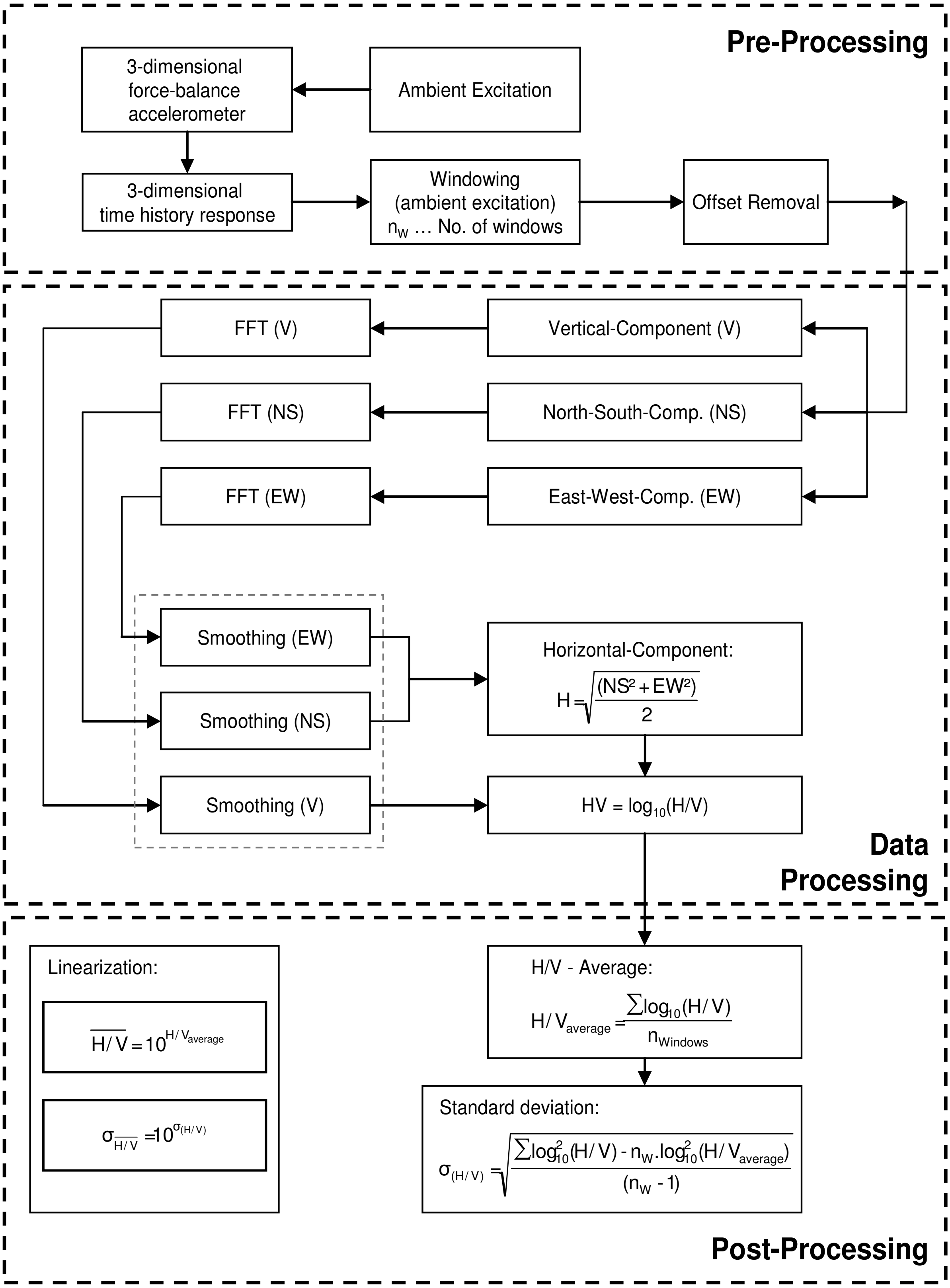

Figure 4: Flowchart of processing the average H/V-Ratio $\overline{H/V}$ and standard deviation $\sigma_{\overline{H/V}}$.

3.3 Shear Wave Velocity V_s

The shear wave velocity V_s and the thickness of the subsoil layers are essential parameters for the accurate determination of site-effects as well as the economic seismic design according to Eurocode 8.
Depending on the local existent soil layers several seismic methods can be used. If the soil impedance *I*, denoted as the product of the wave velocity *v* and the soil density *ρ*, of the upper layer I_1 is smaller than the soil impedance of the subjacent layer I_2, the method of seismic refraction can be used, see Fig. 2.
The seismic waves will be excited with a defined falling weight and registered with a couple of 3-dimensional geophones ranged in arrays on the subsoil surface in defined distances, see 3.1.
In other publications [Havenith, H.B., et al. 2006] different methodologies are used to measure the shear wave velocity. The main advantage of the proposed forced vibration tests is on the one hand the very high quality of the measured data. On the other hand with additional accelerometers inside the buildings very important information about the dynamic soil-structure interaction can be found. Due to the fact that full scale tests are very rare these information are of great relevance and can be used to verify numerical simulations of dynamic soil-structure interaction analysis.

3.4 Vulnerability of Existing Building Structures

The seismic vulnerability of existing building structures is one of the most important steps in an integrated seismic hazard analysis and microzonation study. In particular the evaluation of existing buildings should be as detailed as necessary and as precise and elementary as possible. One of the most important publications in this area of research was done for the city of Basle [Lang. K., 2002]. The general concept of the method based on nonlinear static procedures is to develop a vulnerability analysis and calculate the capacity and seismic demand of the building structures.
This methodology can almost completely be adapted for residential buildings of the microzonation study in Vienna, because of the similar topology of building structures. Other type of structures, like bridges, infrastructure facilities or high rise buildings require a more precisely vulnerability analysis.

4. APPLICATION

The SEISMID technology should led to an integrated seismic hazard analysis method which can be used for different applications. One of the most important will be the development of a microzonation study for the cities Vienna, Graz and Innsbruck.
Furthermore the technology can be used to drive detailed analysis for important building structures with unsteady layouts. It therefore can be used to get detailed soil parameters like the shear wave velocity V_S, dynamic Young's modulus E_{dyn} and others as input for numerical simulations. Bridges are one of the most important and highly vulnerable building structures and are therefore deserved to be protected. In section 4.2 the proposed application of the SEISMID technology on bridges will be described.

4.1 Residential Buildings

The deliverables of the SEISMID technology for urban areas should meet in an integrated microzonation study with several individual utilisable products. Implemented in a Geographical Information System (GIS), the data should be provided in cartographic form, for instance as:

- 3-dimensional geologic map
  Content: Layer thickness, soil parameters and groundwater level.

- Natural frequency of the subsoil
  Content: Natural frequency of the subsoil according to the grid of the accomplished measurements in the investigated area.

- Amplification factor:
  Content: According to the peaks in the H/V-spectra, the lower limit value for the amplification of shear waves can be obtained.

For specific applications the established data sets should be posed in separated maps. On the other hand for public demand the data should also be concentrated in an integrated map. This should lead to an aerial view like map, wherein for each building all measured and calculated data can be easily recalled.
Exemplarily this has been done for single buildings in Vienna, shown in Figure 4. The measured and calculated data are centralised in scheduler form, retrieved by clicking on the several buildings in a publicly available city map.

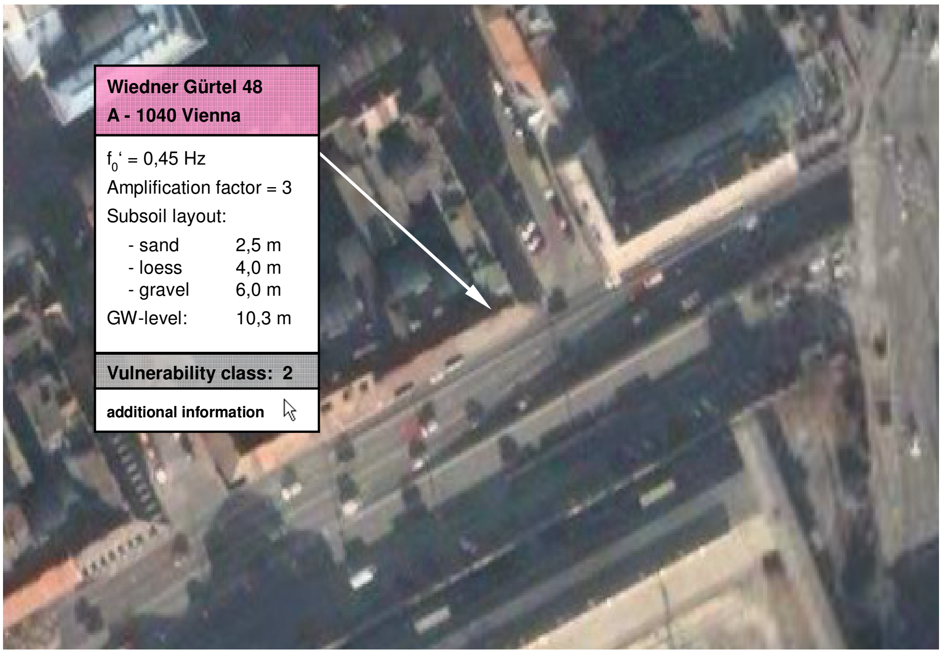

Figure 5: Example of GIS-Implementation of SEISMID date for residential buildings in Vienna.

4.2 Bridges

In many cities bridges are the vulnerable chain link of lifeline infrastructure and often connect several districts. They are therefore one of the most important building structures but unfortunately also one of the most vulnerable ones, for instance the Vienna Donaustadtbrücke, shown in Fig. 6.
Supplementary to the basic investigations mentioned in 4.1, bridges require a more precisely investigation because their supporting elements are often more exposed and exploited than those of residential buildings. It is obviously that they are often based on different subsoil, resulting in different amplification factors for each bearing.
The additional investigations should be concentrated on:

- Brief knowledge of the subsoil parameters at each foundation based on verified measurements (borehole data should be used to compare and update the in-situ measurements)

- Natural frequencies and mode shapes of the bridge deck

- Natural frequencies and mode shapes of supplementary bearing structures (cables, pylon, piers, …)

- Amplification factor for each investigated foundation

- Bearing capacity of the whole structure and several parts (measurements or numerical simulations)

Careful attention has to be paid on the carrying of horizontal reaction forces caused by seismic waves because most bridges are very vulnerable against their horizontal direction.

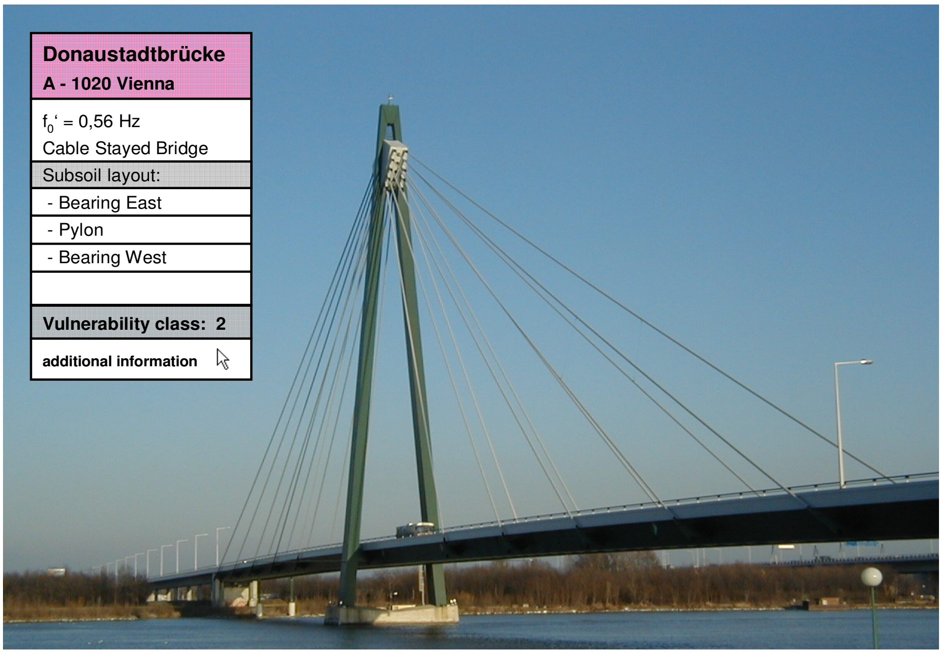

Figure 6: Example of implementation of the SEISMID technology for bridge structures in Vienna.

5. CONCLUSIONS

Local amplification effects of building structures based on soft layered subsoil were well investigated over the last decades. It is a matter of common knowledge that these effects often occur in urban areas with high density of population. The Vienna Basin is one of the most important areas in Austria with about 2.4 million inhabitants and a productivity of about 45% of Austrian GDP. Until now there was a deep lack of investigations of local site-effects in that area, although it was recognised that the seismic hazard is much higher than expected earlier. This fact combined with the high sophisticated international projects has led to the development of a technology for microzonation and seismic hazard assessment for urban areas in Austria, the so called SEISMID-technique.

The SEISMID-technique covers in-situ measurements (ambient and forced vibration tests) to investigate local soil parameters, stock-tacking of existing building structures, validation of vulnerability, assessment of local amplification potential and a combined microzonation-study where all achieved information should be concentrated.

The in-situ measurements comprise ambient vibration tests to identify the local amplification potential and forced vibration tests to gain the local soil parameters. Ambient vibration tests are an attractive method to measure not only the dynamic characteristics of building structures but also the dynamic amplification potential of soft soil layers. The forced vibration tests have the main ambition to get knowledge of the subsoil parameters but can also be used as update parameters for numerical dynamic soil-structure interaction analysis. Therefore the seismic waves are generated by a defined falling weight and registered with 3-dimensional geophones arranged in arrays on the subsoil surface and inside the building structure to measure the dynamic response.

The SEISMID-technique should on the one hand be implemented in a microzonation-study for residential buildings in urban areas in Austria (Vienna, Graz, and Innsbruck). Therefore the extracted information will be implemented in a Geographical Information System (GIS).

On the other hand strongly vulnerable and important building structures like bridges (traffic, public transport, pedestrian, and supply-bridges) have to be protected, thus the SEISMID-technique should not only be restricted for residential buildings. However, for complicated building structures the SEISMID-technique need to be adopted and extended.

Altogether the SEISMID-technique should be a sophisticated procedure for seismic hazard assessment especially in urban areas. It will therefore be a helpful device for ongoing studies and simulations. The proposed method will also help to get the correct design input values for building codes and thus is responsible to save considerable money in critical zones.

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